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Harvazinski, M., Shipley, K., Talley, D., Sankran, V., Anderson, W.

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10 E. Saturn Blvd
Edwards AFB CA 93524-7680

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Edwards AFB CA 93524-7048

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14. ABSTRACT
The current study describes two modeling approaches to model an unstable seven element linear array of shear coaxial injectors. The first approach is a reduced model where the driving injectors are replaced with an artificial forcing term. The forcing amplitude can be adjusted so that the effect of the transverse instability on the center study element can be examined parametrically. The second approach models the entire domain, and can capture additional details such as the inter-element interactions and the self-excited nature of the instability. Both sets of results are compared with experimental measurements and used to provide physical insights into the underlying instability mechanisms.

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Computational Modeling Approaches for Studying Transverse Combustion Instability in a Multi-element Injector

Matt Harvazinski[1], Kevin Shipley[2], Doug Talley[1], Venke Sankaran[1], Bill Anderson[2]

[1] Air Force Research Laboratory

[2] Purdue University

History

Combustion instability is an <u>organized</u>, <u>oscillatory</u> motion in a combustion chamber <u>sustained by combustion</u>.

CI caused a four year delay in the development of the F-1 engine used in the Apollo program

> \> 2000 full scale tests
> \> $400 million for propellants alone (2010 prices)

Irreparable damage can occur in less than 1 second.

Damaged engine injector faceplate caused by combustion instability

"Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs"

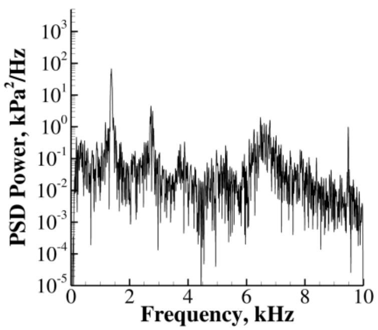
– JANNAF Stability Panel Draft (2010)

Overview

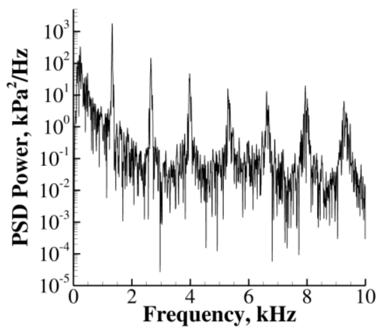
- **Review of single-element simulations**
- **Multi-element experiments**
- **Modeling approaches**
- **Results**
  - Approach 1 – reduced model
  - Approach 2 – complete model
- **Summary**

Single Element Studies

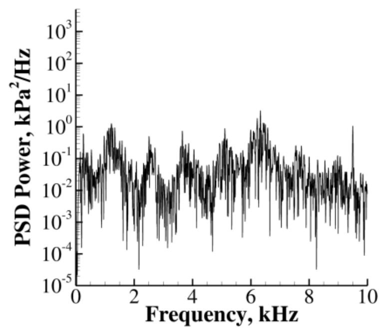
Short Post
Marginally Stable



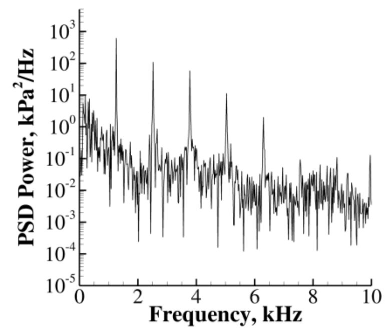
Intermediate Post
Unstable

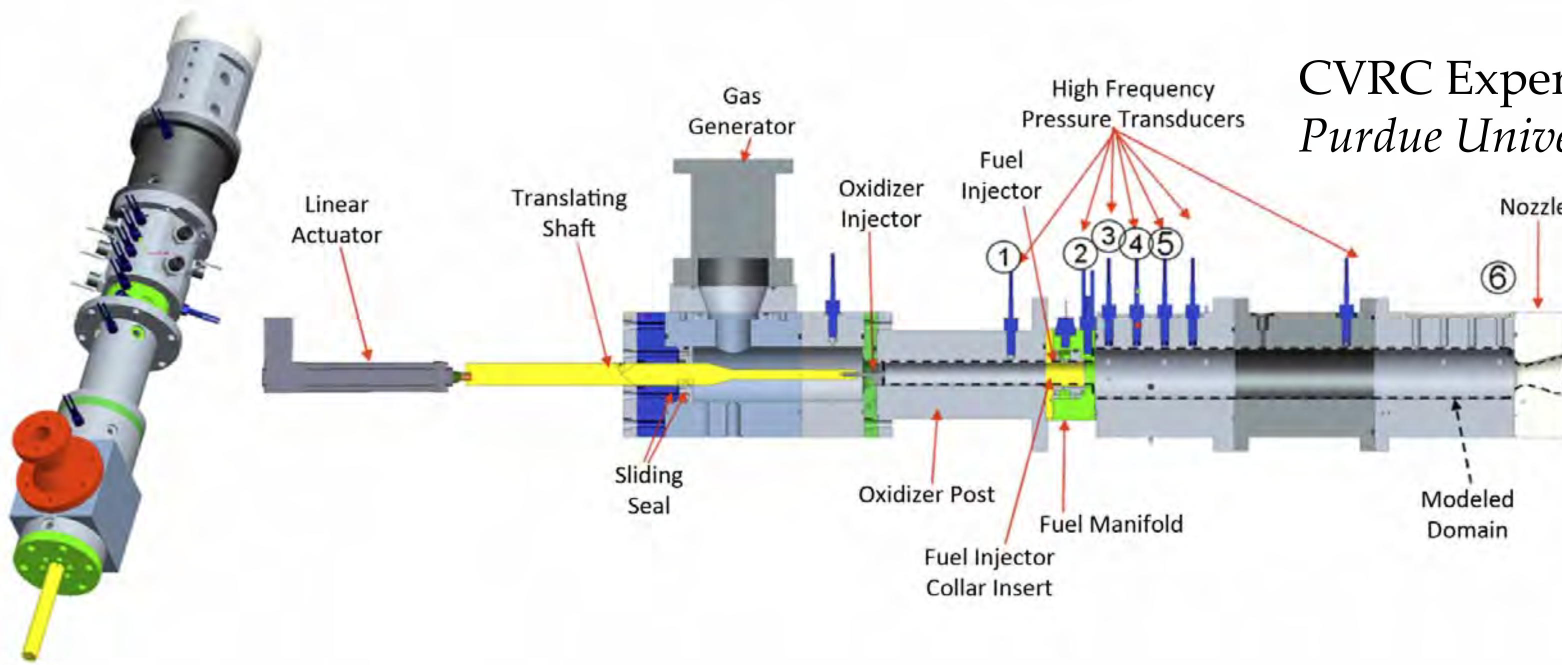


Long Post
Stable



Long Post
Unstable

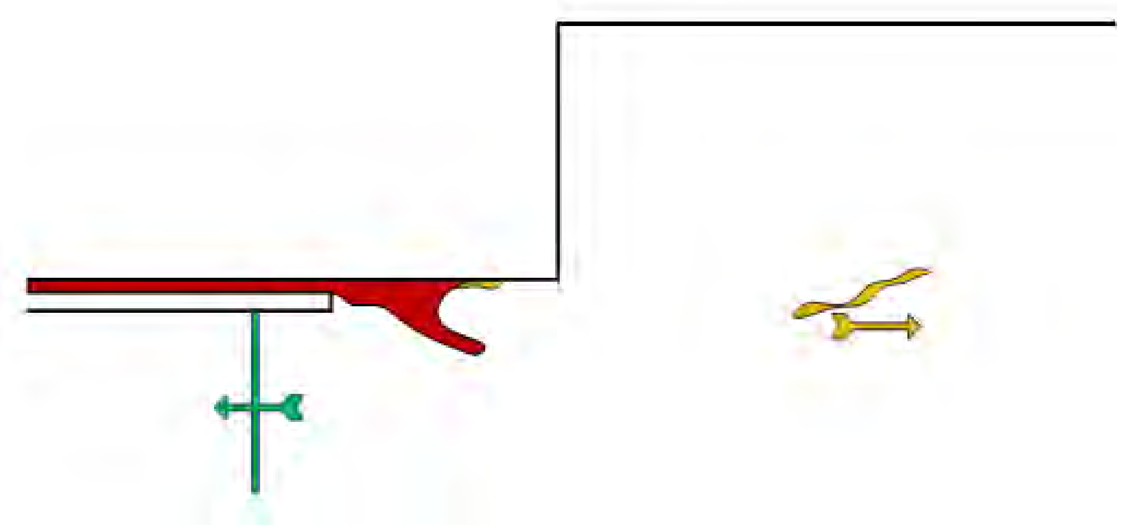




CVRC Experiment
Purdue University

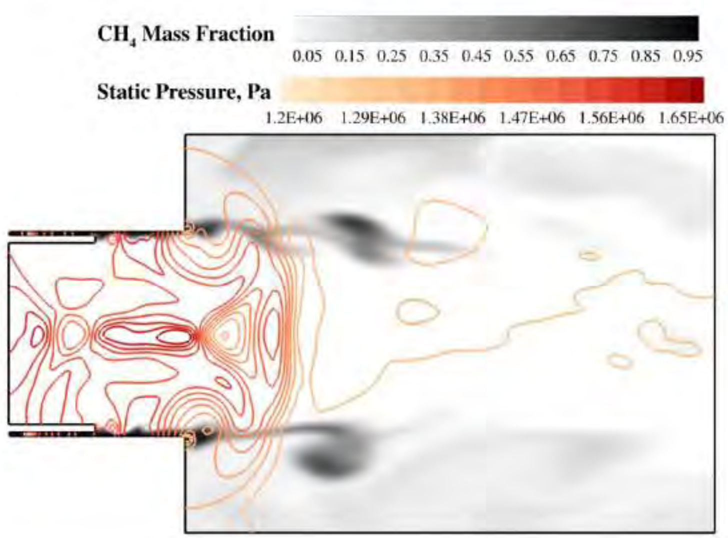
Instability Mechanism

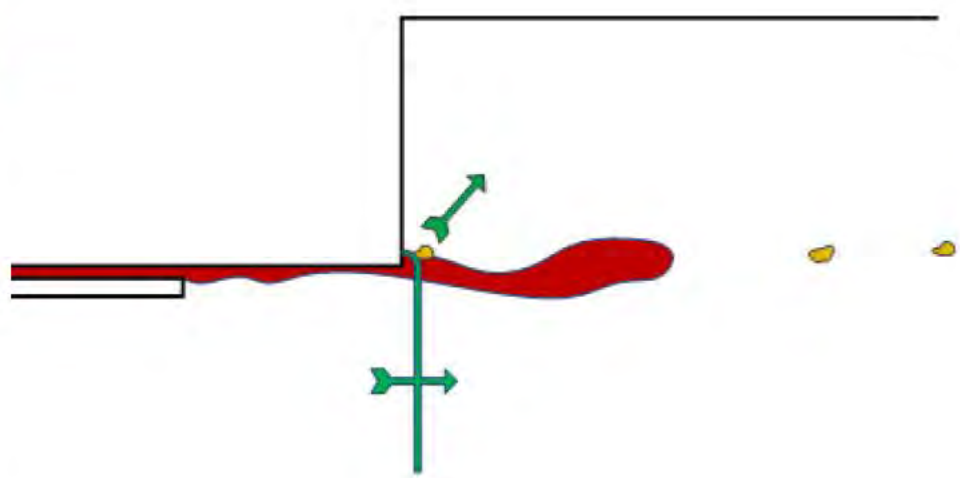
- A series of 3D simulations for the short, intermediate, and long post lengths was completed to identify the instability mechanism.
- The marginally stable short length showed continuous heat release
- The unstable results were the result of a fuel cut off event.



Instability Mechanism

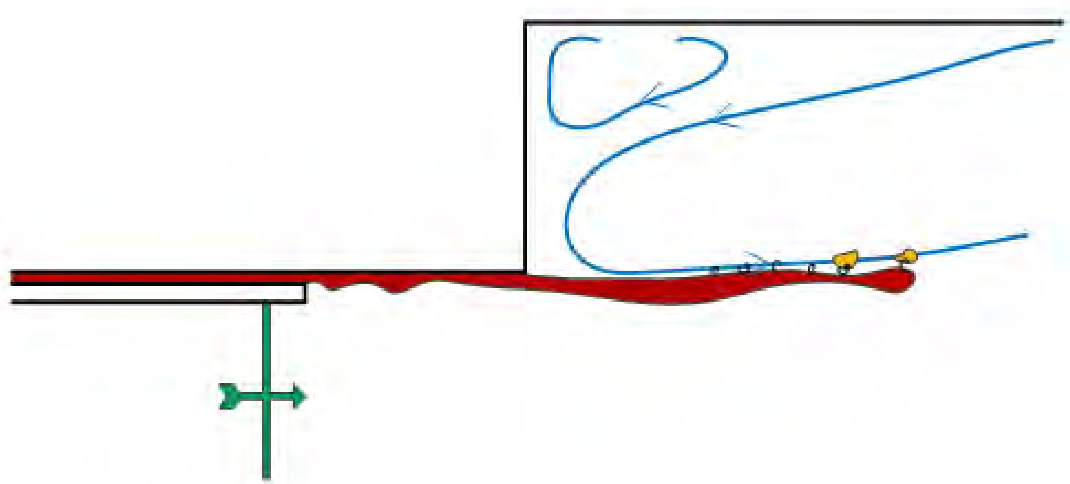
- **For the intermediate length combustion was reinitiated when the returning oxidizer post wave pushed the accumulated fuel into the warm recirculating gases**





Instability Mechanism

- For the long length combustion was reinitiated later in the cycle and was the result of mixing between the recirculating gases and the accumulated fuel
- Simulations only predicted the unstable long length
- Experimentally this length showed the most variability

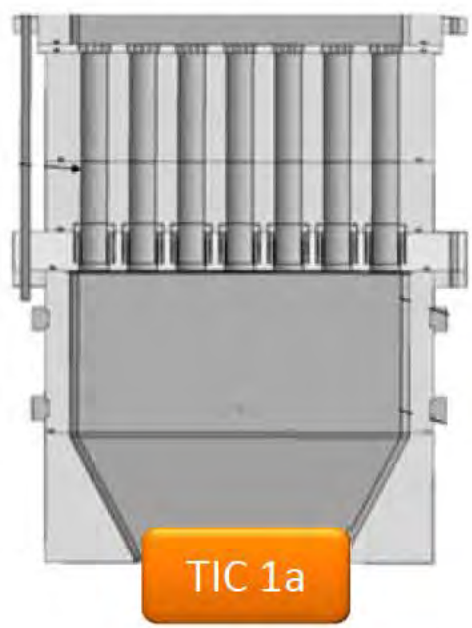


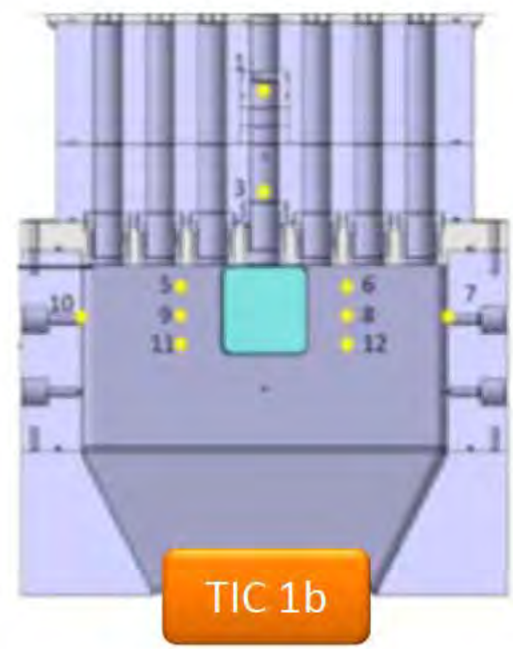
Single & Multi-element Studies

Single Element	Multi-element
• Less expensive • Smaller domains	• More expensive • Larger domains • Complex geometries
• Substantial work published	• Less literature, limited work
• Wall effect is exaggerated	• Captures inter-element interactions

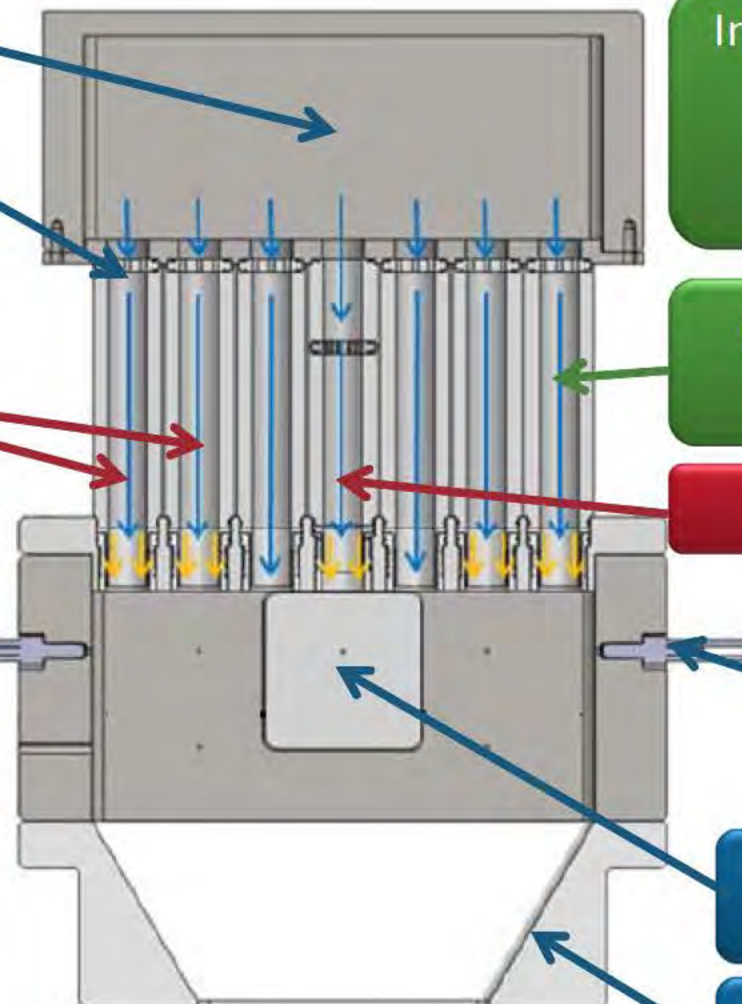
Transverse Instability Combustor

- Transverse Instability Combustor – TIC
- Experimental rig developed at Purdue University
- Four major iterations to date
- Rectangular chamber with 7 elements
- Linear array of 7 elements
- Injectors are similar to the single element work
- Instability is self-excited





TIC Configuration



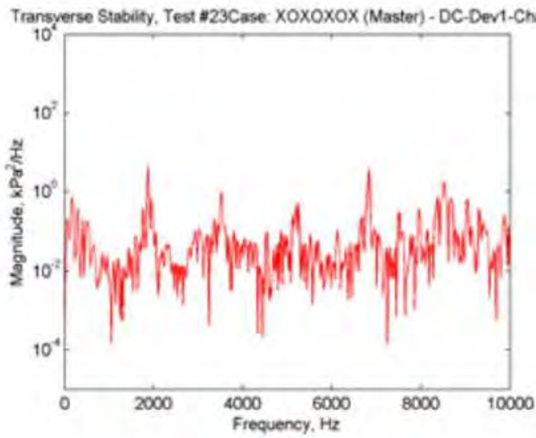
Dual Purpose Experiment:

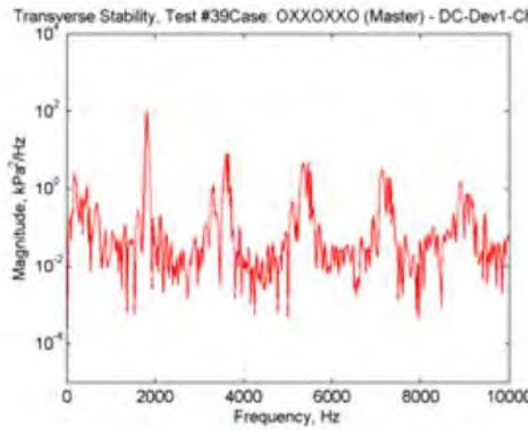
1. Self-excited transverse instability
2. Observe combustion response of the study element to high amplitude transverse instabilities

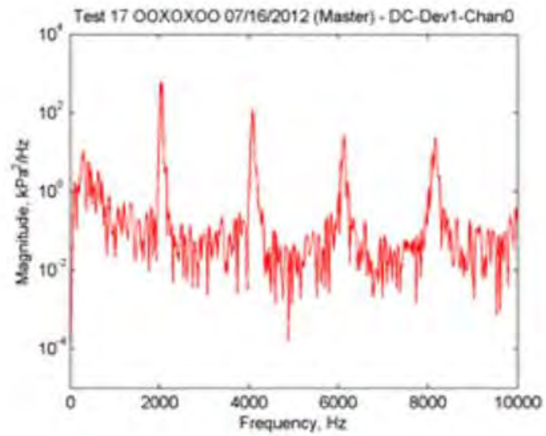
TIC Experiments

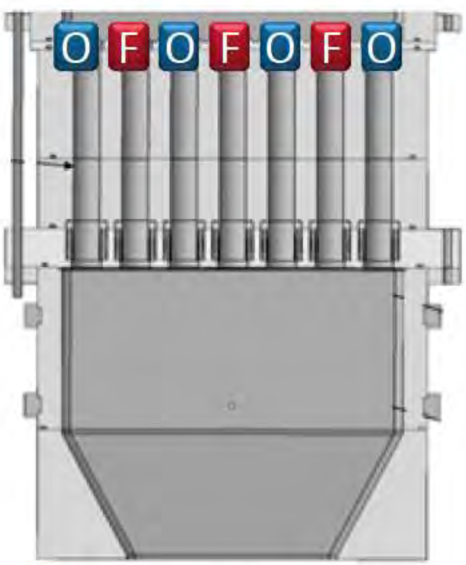
		TIC 1a	TIC 1b	TIC 1c	TIC 1d
Oxidizer		H_2O_2	H_2O_2	H_2O_2	H_2O_2
Fuel	Driving	JP-8	RP-1	CH_4	CH_4
	Study	$C_{12}H_{26}$	C_2H_6	CH_4	CH_4
Oxidizer Inlet	Driving	Perforated Plate	Perforated Plate	Perforated Plate	Choked Venturi
	Study	Perforated Plate	Choked Slots	Choked Slots	Choked Venturi
Notes		Two-phase flow		Multiple study ox-post lengths considered	Multiple ox-post lengths considered
Companion Simulations			3-element	7-element	Future Work

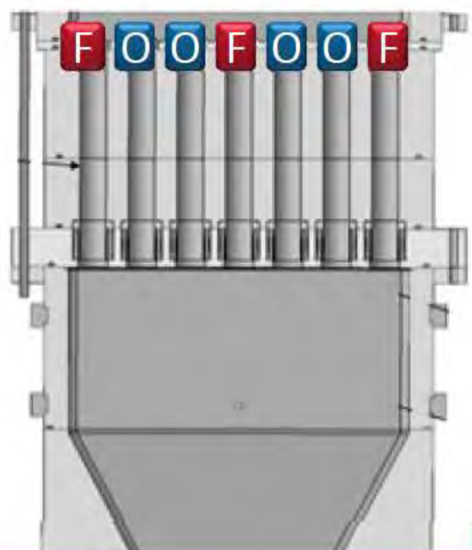
Amplitude Control – TIC 1a&b

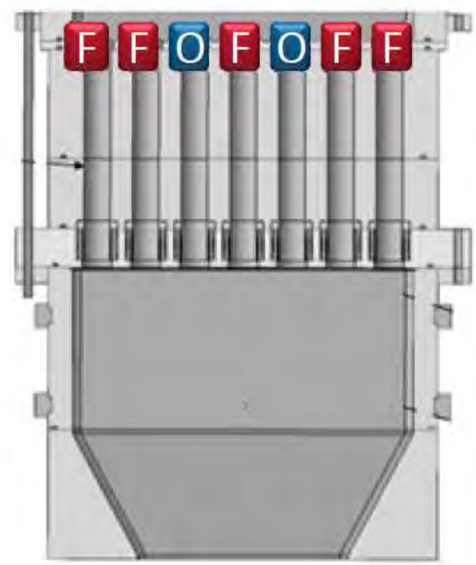


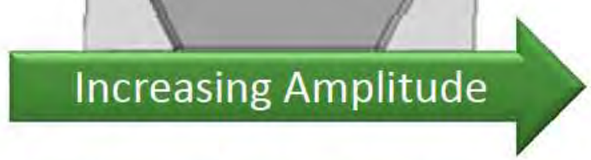








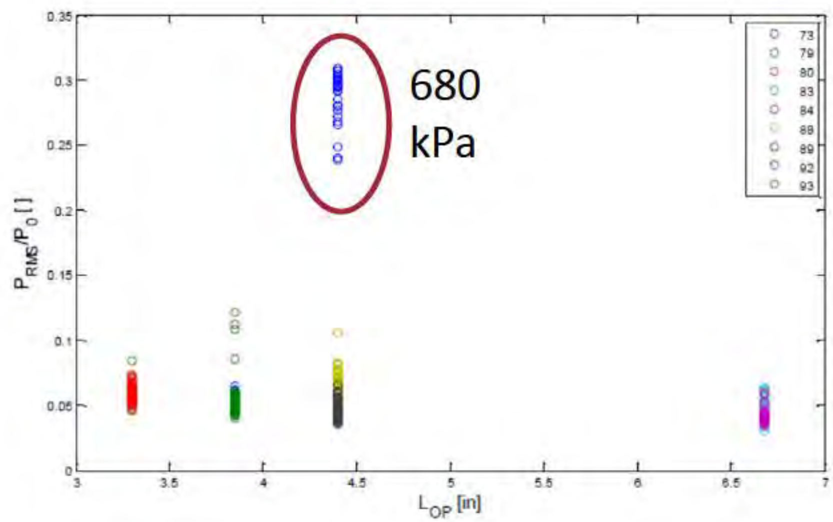


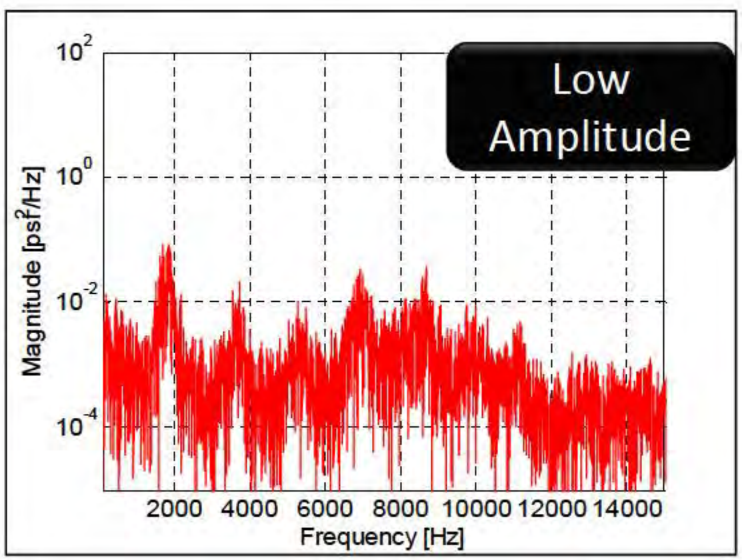


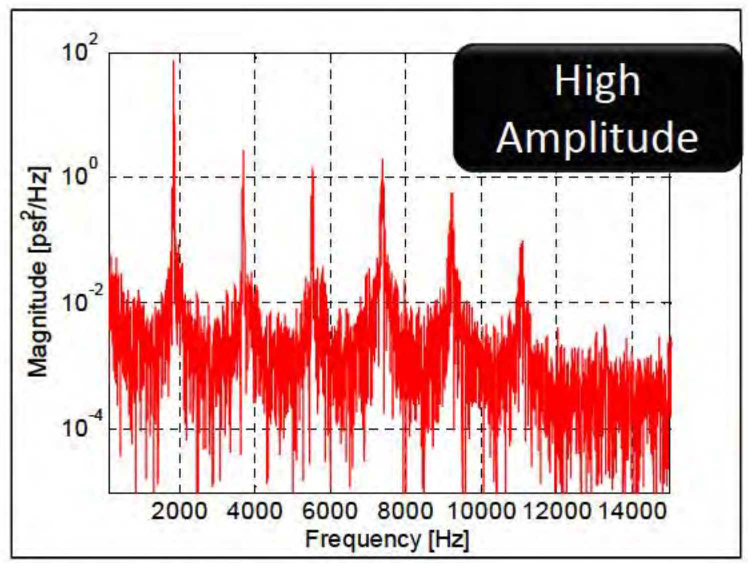
F - Fuel & Oxidizer
O - Oxidizer Only

Amplitude Control – TIC 1c&d

- **Length of the study element proved to be largely unimportant**
  - Low < 170 kPa
  - High > 680 kPa







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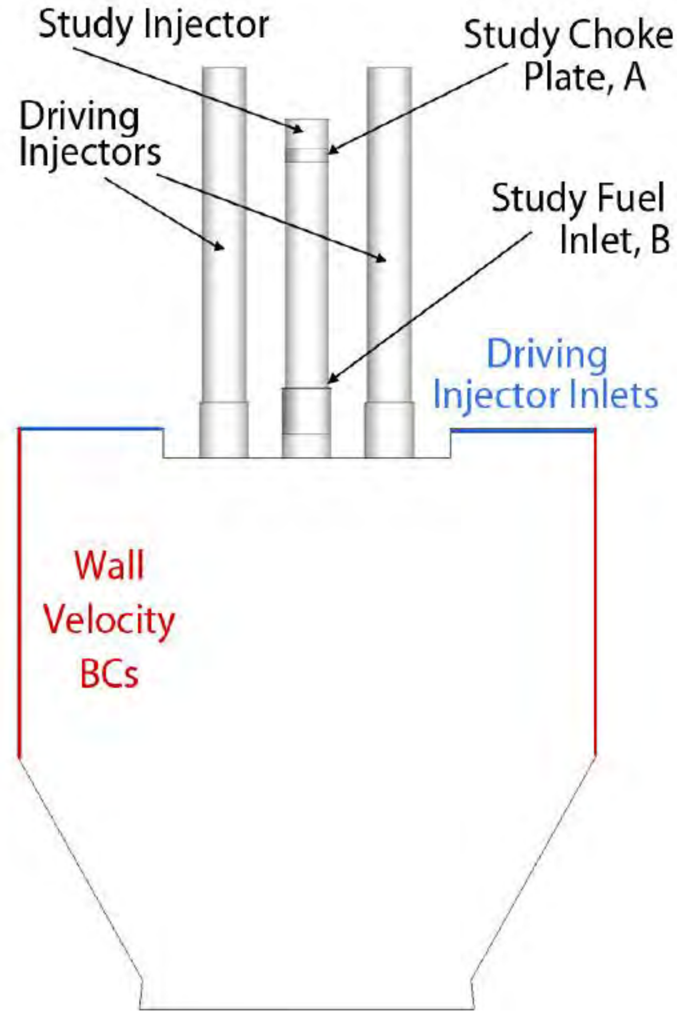
Two Distinct Modeling Approaches

Full Simulation	Reduced Model
• Captures self-excited instability	• Does not capture driving
• Captures inter-element interactions	• Limited inter-element interactions
• Amplitude is difficult to control	• Amplitude is prescribed
• Expensive	• Low cost

Virtual Injector Screening Tool

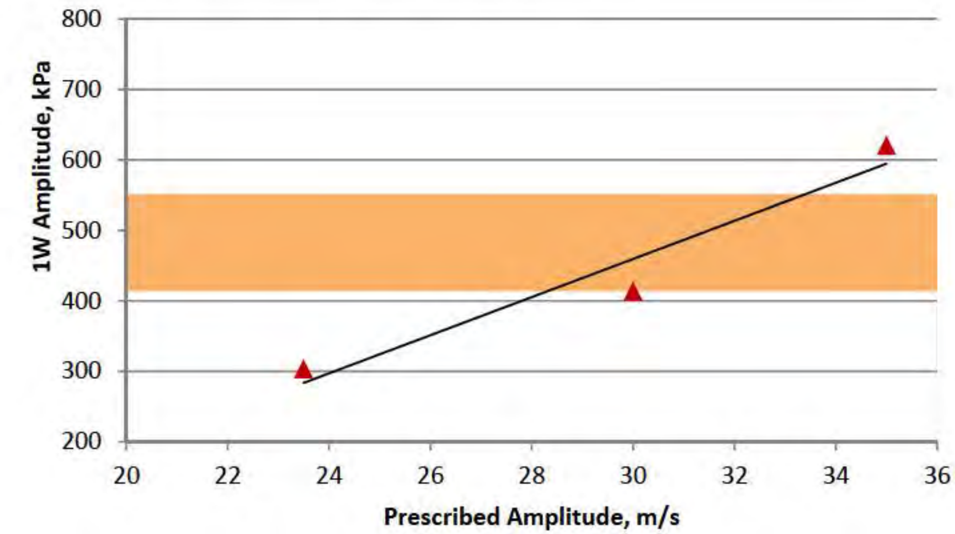
- **The reduced model can be used as a virtual injector screening tool**
- **The element of interest is subjected to forcing and the response is observed**
- **An artificial boundary condition us used to drive the instability**

$$u_{\text{wall}} = A\sin(2\pi f + \varphi)$$

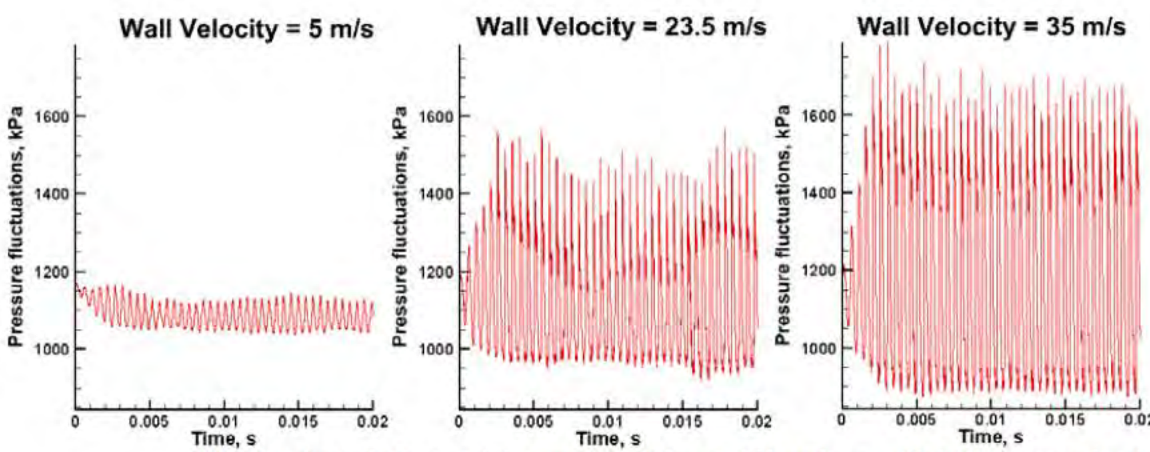


Amplitude Control

- **The amplitude is tunable**

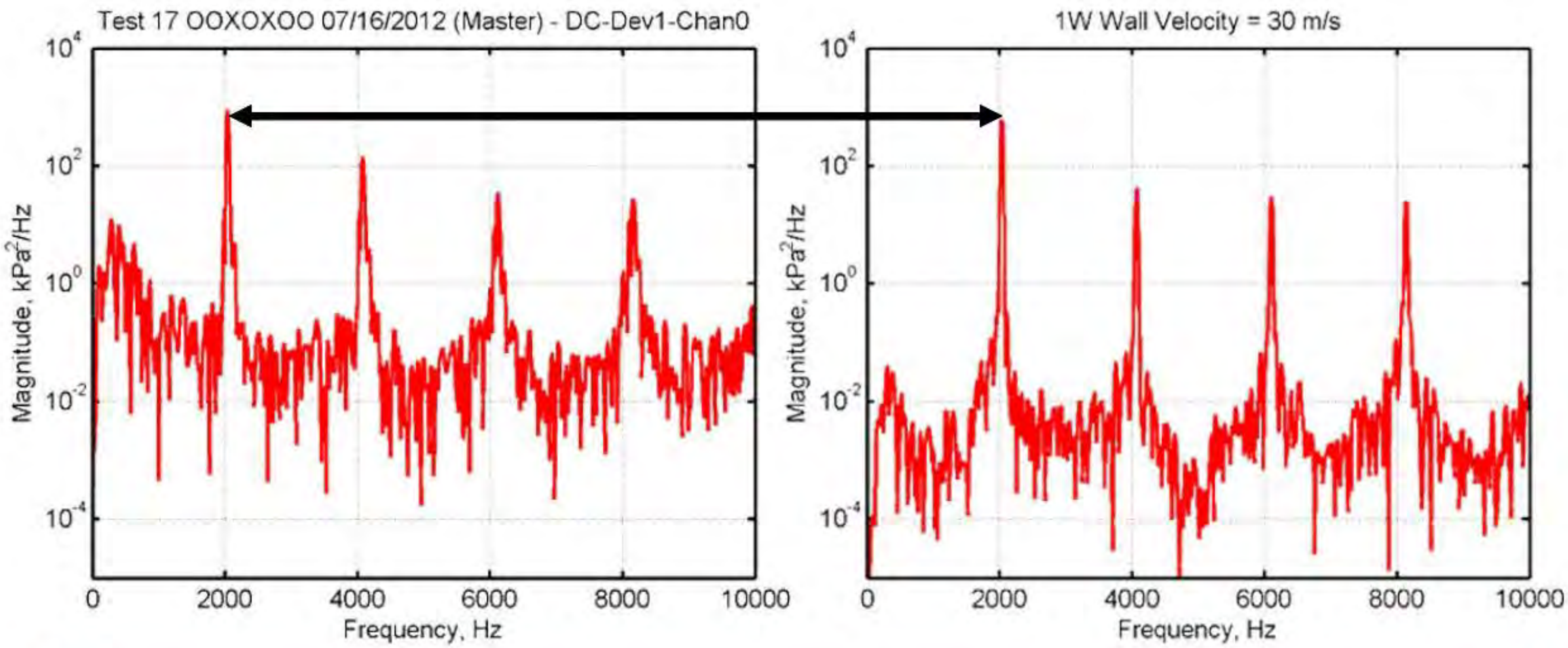


Targeted Amplitude



Observed Wall Pressure

Comparison to Experiments

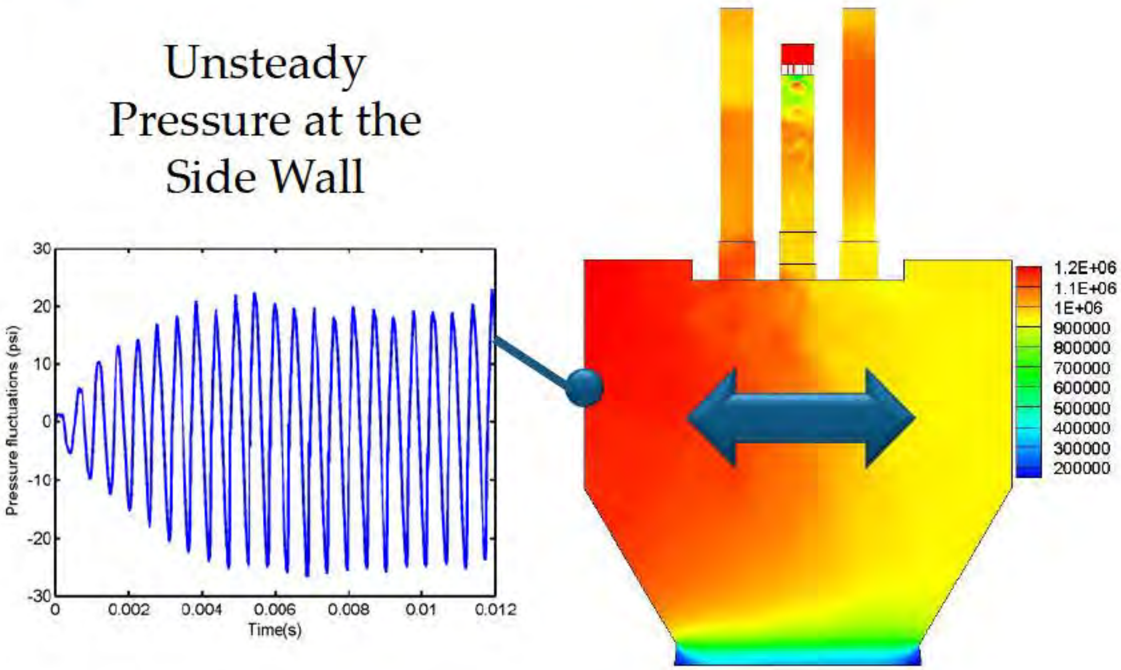


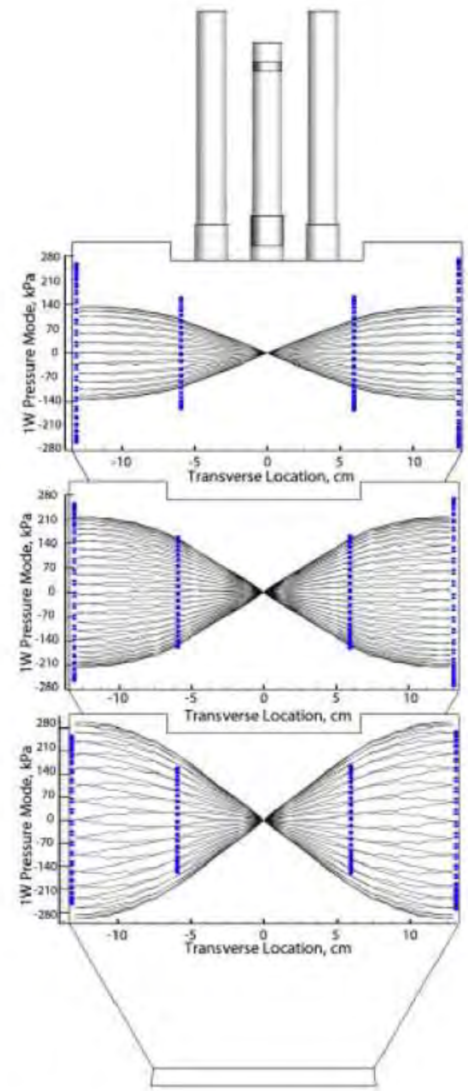
An excellent comparison to the experimental results can be achieved by prescribing a single sine wave

Combustion Response

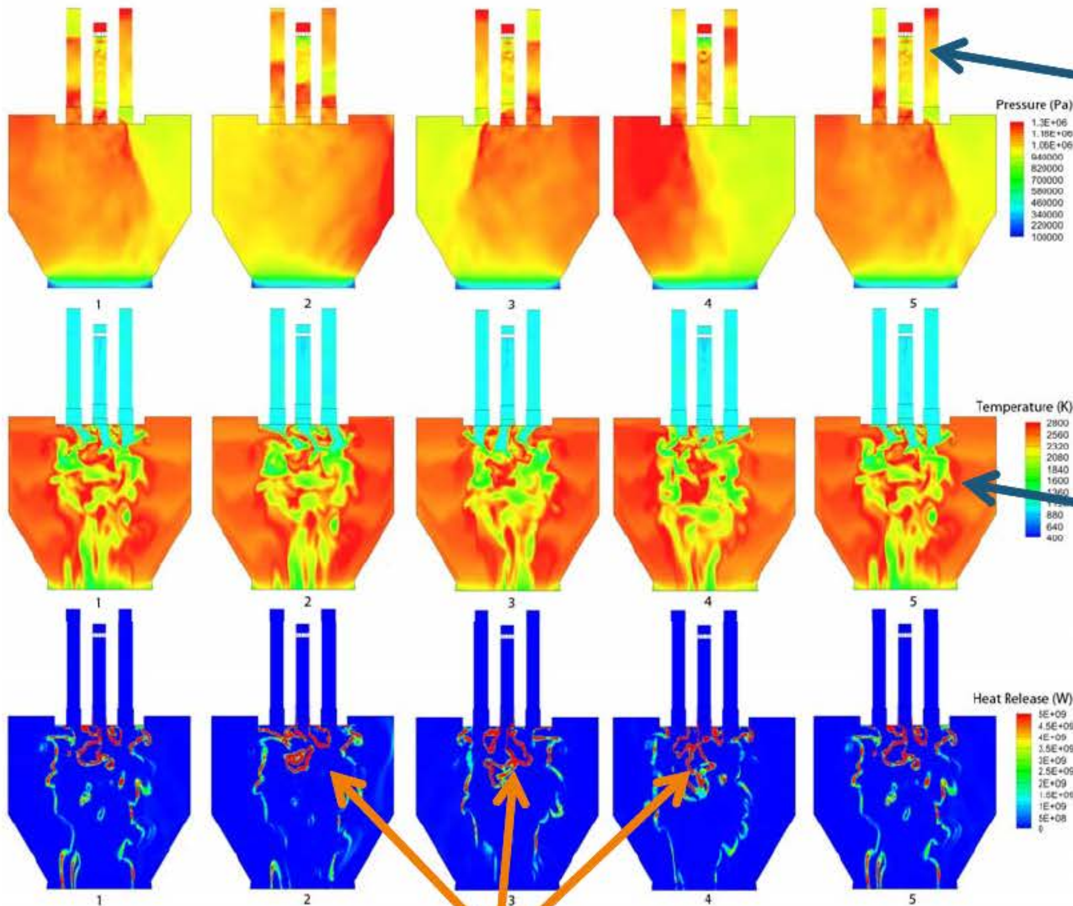
Observer the effect of transverse oscillations on the study element

Unsteady Pressure at the Side Wall





Cycle



Acoustic coupling visible in the side elements

Temperature in the side region is artificially high from the imposed boundary condition

Heat release oscillates with pressure wave

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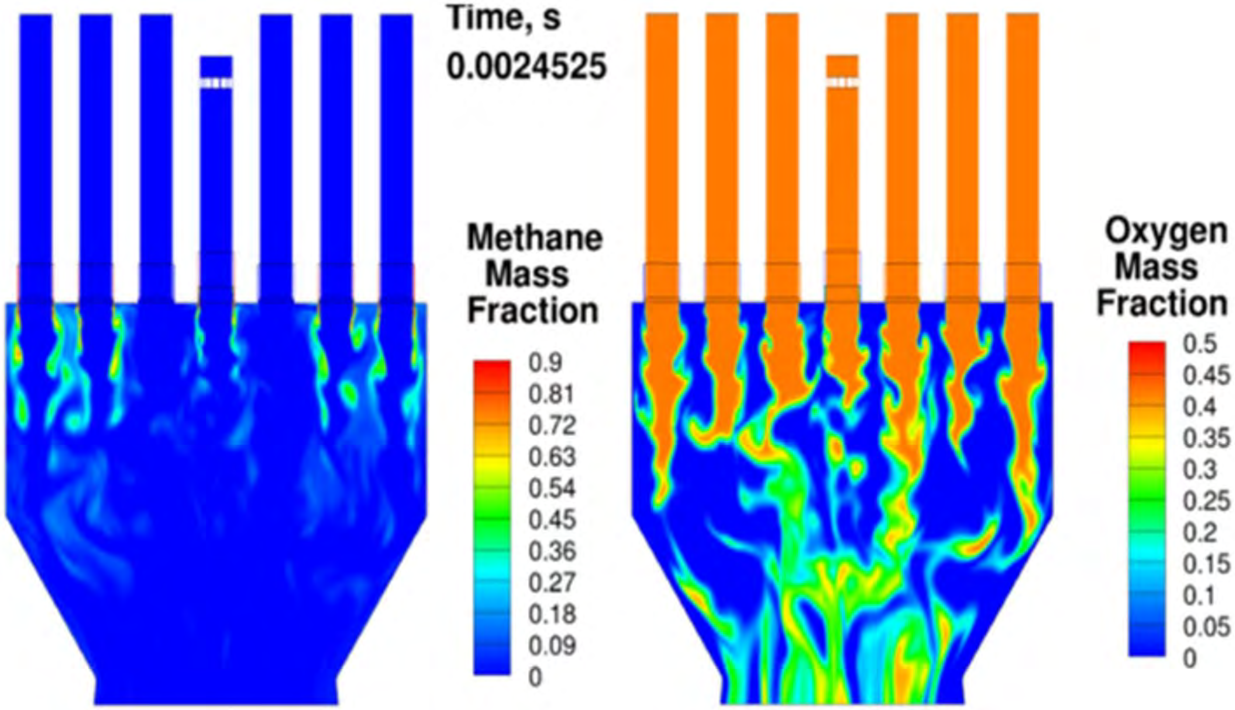
Seven Element Simulation

- **Considerably more expensive based on the added grid points for the additional elements**
- **Simulation captures the self-excited nature of the experiment, inter-element interactions**

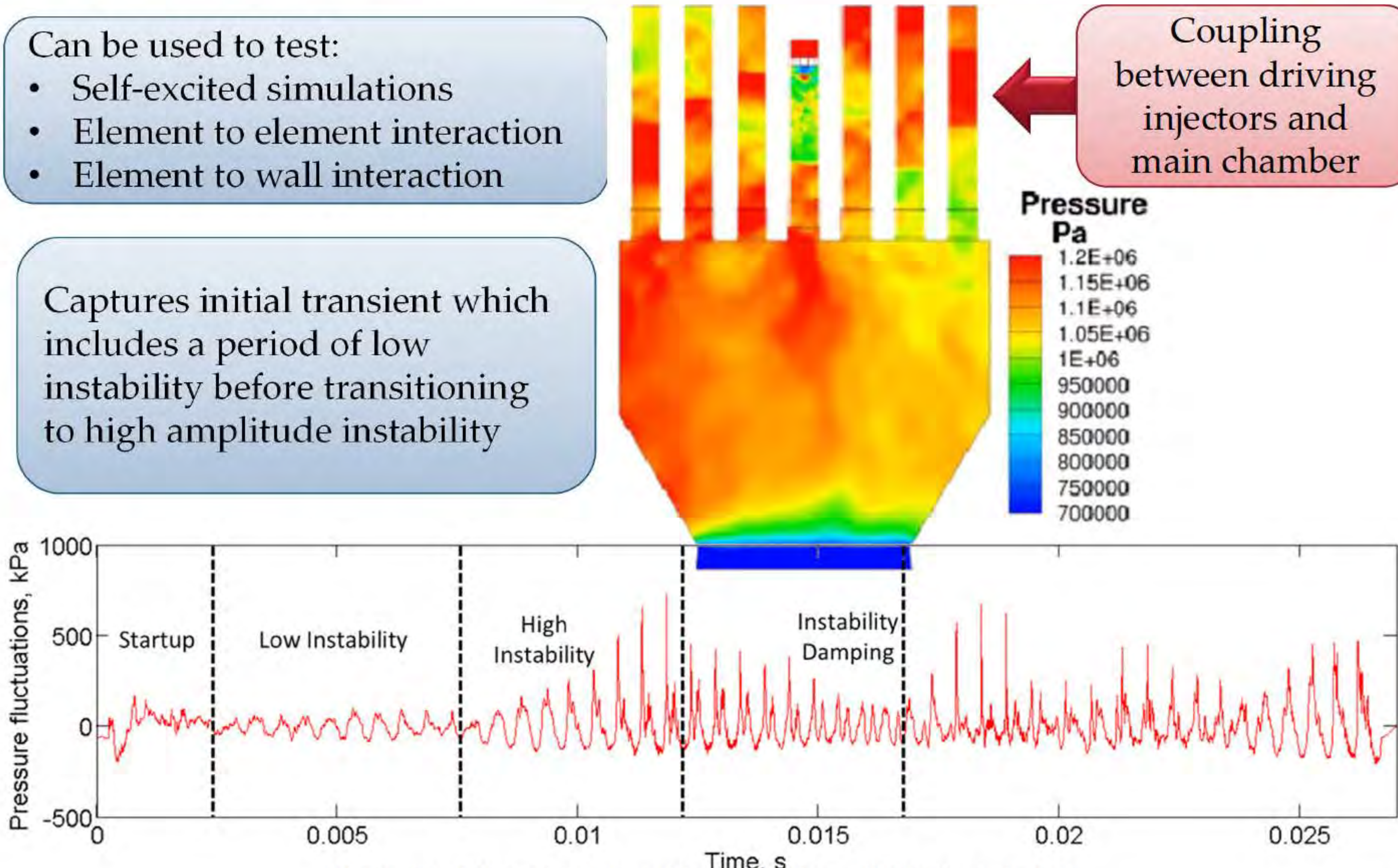


Self-excited Simualtion

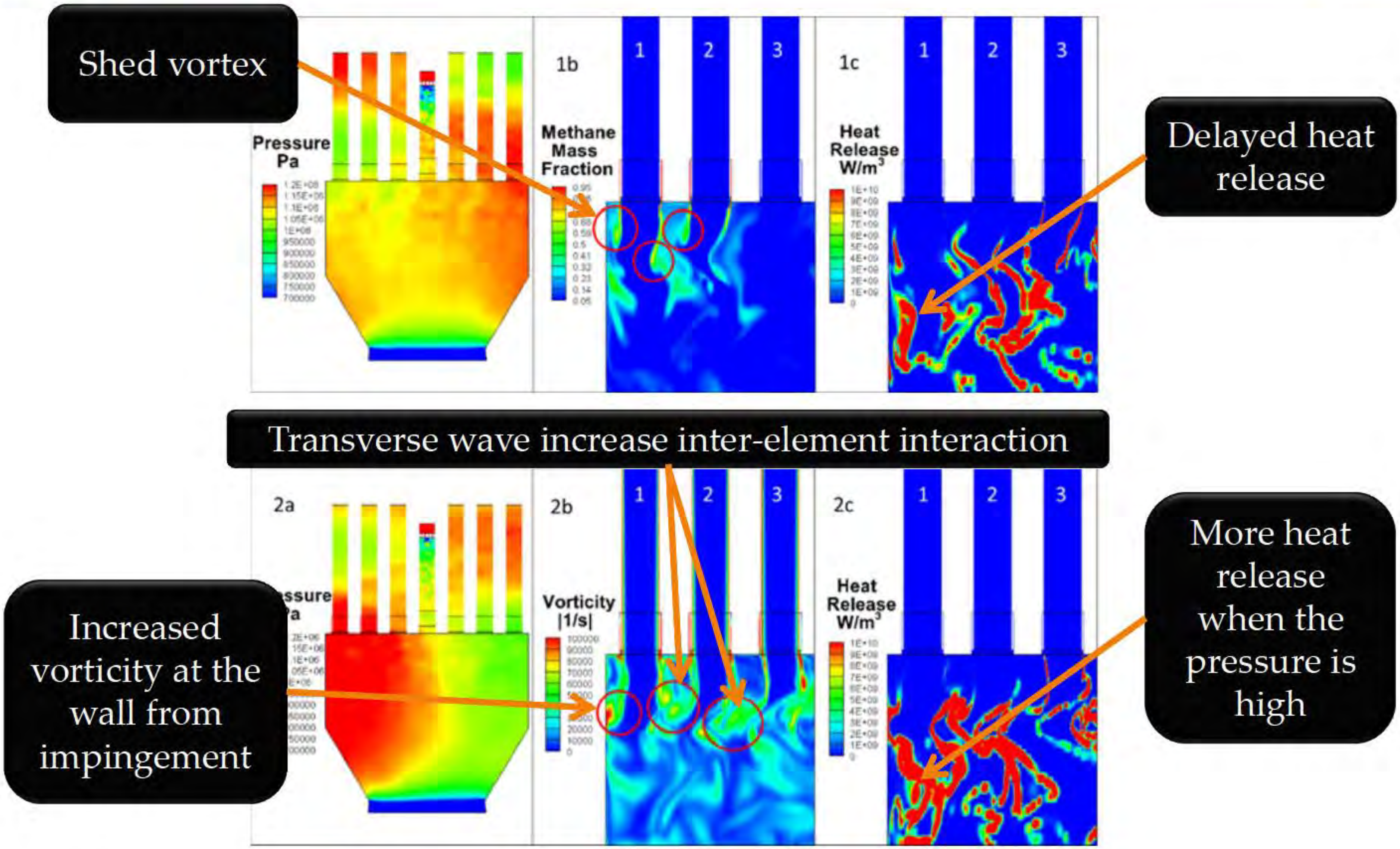
Can be used to test:
- Self-excited simulations
- Element to element interaction
- Element to wall interaction

Captures initial transient which includes a period of low instability before transitioning to high amplitude instability

Coupling between driving injectors and main chamber



Inter-element Interactions



Summary

- **Two modeling approaches were presented for modeling transverse instability along with a sample result of each**
- **Virtual injector screening tool**
  - Observe the injectors response to excitation in a controlled environment
  - Precise control of amplitude, frequency
- **Full Simulation**
  - Captures self-excited transverse instability, inter-element interactions
  - Coupling between injectors and the main chamber

Future Work

- **Modeling TIC 1d**
  - Attempting to capture what happens when the length of all injectors are changed
  - Preliminary experimental suggest that different amplitude are obtainable
  - The unstable single element length showed stable combustion in the transverse chamber! This is unlike prior results.